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Implications of 'Power by the Hour' on Turbine Blade Lifting

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Summary

'Power by the Hour'® engine sales contracts are becoming popular both amongst engine operators and engine manufacturers. This paper examines how accurate turbine blade life prediction is achieved and is combined with accurate measurement of damage in service for successful contract fulfilment.

Introduction

'Power by the Hour' engine sales contracts are becoming popular amongst engine operators and engine manufacturers, (1). This type of contract requires detailed assessment of the life cycle costs of the overall engine, and more specifically the individual modules and components therein. An example of a typical life cycle cost breakdown is shown in figure 1.

The turbine module, where blades are operating at high temperature under high load, is a critical area that can significantly influence the overall engine life cycle costs. The accurate prediction of turbine blade life at the design stage is therefore necessary to allow the life cycle costs to be estimated, and thus to influence the contractual discussions at the earliest possible stage. The life cycle cost estimates are used to judge the balance between life, cost and technical specification (e.g. performance and weight) of the blade. On release of engines into service, monitoring of engine usage is necessary to ensure that the blades are performing well with respect to the damage usage rate per hour and that the initial assumptions of aircraft operation were correct.

This paper reviews how 'Power by the Hour' contracts require accurate turbine blade life prediction, combined with accurate measurement of damage in service for successful contract fulfilment.

What is 'Power by the Hour'?

A 'Power by the Hour' contract implies that the engine operator will buy a fleet of engines, but will not purchase spare engines. The engine manufacturer then agrees to supply spare engines, accessories or modules when required, and to perform all the maintenance work required on the fleet of engines. The rate paid by the customer is charged per flying hour, and the manufacturer would then be expected to carry out all the required maintenance of these engines. This transfers much of the technical risk onto the engine manufacturer, and although providing the opportunity for profits from spares and overhaul operations, clearly requires careful setting of the appropriate hourly rate. This in turn requires accurate life cycle cost estimates that rely heavily on accurate life prediction. From a customer point of view it offers a way of budgeting for the operation of the fleet of aircraft, whilst providing guaranteed availability of engines and a continuous warranty.

The manufacturer is really selling component damage accumulation at an agreed rate over the life of the component. The customer gains an advantage if he exceeds the operating conditions, by opening the throttle more or longer than agreed in order to reduce his mission time. Or perhaps the throttle movement may be a genuine attempt to obtain a given guaranteed level of thrust at a condition. It is only by measuring the damage accumulation that sensible conclusions can be reached. This requires accurate prediction of modes of damage or failure for the blade, and accurate measurement of damage accumulation in each of these modes.

Modes of Blade Failure

Before discussing the methods used for the assessment of blade life it is necessary to briefly review the prime modes of failure for both substrate and coating, see figure 2. Modes of failure that lead to wear out rather than loss of integrity of the blade are considered. For this reason blade failure from high cycle fatigue or integrity cracking of coatings, which are assumed to be designed out prior to entry into service, are not considered.

Blades have a finite life due to the arduous conditions in which they operate. They will require replacement before their mechanical condition deteriorates to the point of failure or has a severe impact on the performance of the engine. Deterioration can result from the separate or combined application of mechanical and thermal loads or the effects of environmental degradation. Turbine blades, particularly those from the high pressure turbine, are subjected to a combination of high mechanical loading due to the high speed of rotation and the transfer of gas loads through the blade into the disc, and high thermal loading caused by high temperatures and steep thermal gradients in the blade (2). The high temperatures and temperature gradients are initially the result of radial variations in the gas stream temperature leaving the combustion system that produces a peak of gas temperature around the mid-height of the blade, combined with the pressures and flows that result in high heat transfer to the blade. However the magnitude of the gradients is often made worse by the internal cooling system of a cooled blade, which is primarily introduced to reduce the mean metal temperatures, and then tuned to minimise the peak temperatures. Uncooled blades have significantly lower thermal gradients, reducing the degree of thermal strain contribution.

The prime failure modes are as follows:

1. Creep - permanent deformation that occurs as a result of the application of mechanical and thermal loads that are held over a period of time at high temperature (3). In uncooled and lightly cooled blades this can result in a blade length increase combined with a reduction in cross sectional area due to build up of dislocation mechanisms. If allowed to progress, this ultimately leads to rupture across the whole aerofoil

section. In cooled blades creep tends to be more localised and leads to crack initiation and propagation.

2. Low cycle fatigue - occurs due to the repeated application of thermal and mechanical loads resulting in stress and temperature cycles that can be of high magnitude but are at low frequency. This cycling leads to the initiation and propagation of cracks. In the blade aerofoil, where the prime driver is thermal strain, cracks may initiate in any one of many locations, figure 3. These locations are mostly associated with local hotspots or strain concentration features such as film cooling holes. These cracks may propagate under the mechanical loads, or in some cases remain benign for a significant proportion of the blade life. In other areas of the blade such as the shroud, shank or root, cracks may initiate and propagate due to the load controlled mechanical stresses that are not relieved as the crack grows.

Any of these aforementioned cracks may reach a critical length, and then propagate rapidly under the influence of dynamic strains or reach a point where ultimate failure occurs and a portion of blade is lost.

3. Surface attack - takes the form of oxidation or hot corrosion, and results in the progressive loss of material with time exposure to the environment. In the case of oxidation or accelerated hot corrosion the rate of material loss increases rapidly at temperatures above 1050°C. Oxidation produces a thin layer of oxide on the surface, which under thermal-mechanical cycling undergoes microscale rupture, leading to spallation (4), figure 4. This process is repeated, with progressive loss of material until a predefined limit is reached whereupon the blade would be rejected at the next overhaul. There are lower temperature forms of corrosion which, together with accelerated oxidation, are to some degree dependent on the presence of salts or sulphur in the gas stream. These are referred to as Type I and Type II hot corrosion (5).

An additional means of surface degradation is through erosion. This is usually a result of particulate impact on the blade leading edge, but is not a common failure mode, although it may become so as the times to failure under other failure modes are improved. An example of the cause of erosion would be shedding of carbon particles from the combustion system.

4. Coating Failures - most hot gas washed surfaces are coated to protect against oxidation and hot corrosion. The presence of a coating results in additional failure modes specific to the coating. The process of failure due to oxidation and hot corrosion of the coating is similar to that outlined in the previous section for the bare material, figure 6, but an additional failure can occur through usage of the thermal mechanical fatigue life of the coating. This results in the initiation of small cracks in the coating, which may propagate along the interface, resulting in loss of coating material, or more commonly, propagate into the substrate material. Early failure due to exceedence of the coating fracture strain is deemed to be an integrity issue.

5. Thermal Barrier Coatings (TBC's) - introduce further potential failure modes (6). In most cases the ceramic coating will have a bondcoat, an oxidation resistant coating. After a period of time the bondcoat can oxidise and result in a lack of adhesion due to the build up of oxide layer, which is the most likely reason for spallation in a mature coating during cycling. The development of bondcoat cracks which propagate along the interface during cycling can also result in spallation of the ceramic topcoat. Similar to basic coatings, the ceramic topcoat will have integrity issues that can lead to cracking.
6. Combined Modes - individual modes of failure can in some cases combine to reduce the life to below that of either of the individual modes (7). In this case an understanding of the interaction between these modes is required. An example is the interaction between creep and fatigue which can result in a significant reduction in life of cast materials. Other examples would be loss of coating leading to substrate oxidation and cracking, or stress corrosion fatigue where the fatigue life is reduced by the presence of corrosion.

Methods used for Life Prediction

Life estimation for turbine blades involves the use of an integrated system that employs Rolls Royce 'Turbine Blade Lifting Methodology' (TBLM) to assess life in the principal modes of failure. The integrated system provides a slick system with many automatic features, which sits within the Turbine Key System, a computing environment across all functional disciplines. This enables a significant reduction in the time taken to perform a life assessment, an improved user interface, an increased quality in life assessment through harmonisation of methods across the company, and most importantly an environment receptive to improvement and update of lifting methods. The lifting methodology has been verified by material characterisation on specimens and blades, by programmes of life assessment on demonstrator engines and by thorough validation against development and in-service experience.

The integrated system performs the following:

1. imports the geometric definition of the blade
2. automatically meshes the geometry using finite elements for thermal and mechanical analysis
3. allows application of the thermal and mechanical boundary conditions
4. solves the thermal problem to provide the temperature distribution
5. automatically accesses physical property data required for the solution of the mechanical problem to obtain the mechanical stresses and strains
6. post-processes these results to obtain the average blade life using a database of lifting algorithms for each failure modes
7. produces graphical and tabular output of lifting data
8. performs a statistical estimate of the whole set life

This method can be applied to both 2-dimensional (2D) models that represent cross sections of the turbine blade, figure 7, and to 3-dimensional (3D) models that represent the full blade geometry. When lifting the aerofoil it is common practice to perform analyses for each failure mode separately and then to combine the failure mode

assessment where appropriate. The following sections describe how each failure mode is treated.

2D Life Assessment

A fatigue assessment employs an elastic 2D generalised plane strain method that is essentially an in-plane model with out-of-plane loads applied. The finite element model yields the cyclic variation in stress and strain at each node from the cyclic variation of thermal and mechanical boundary conditions. These results are then automatically post-processed to extract the major and minor cycles. In each cycle the maximum strain range and peak temperature is determined and the life is predicted using low cycle fatigue behaviour algorithms based on strain controlled data. The strain range may be modified to include a dynamic strain due to vibration, and to account for the influence of any localised stress concentration such as film cooling holes, internal cooling ribs or pedestals. Further correction of the strain cycle is made by taking account of the location of the minimum and maximum strains of the cycle, and is done automatically by an R-ratio correction. This variation has been established from a database of material specimen tests at different R-ratios, to which an algorithm has been fitted to define the equivalent zero to maximum strain cycle. Miner's rule is then used to calculate the total life at each nodal point by accumulating the damage from each of the individual cycles. This is repeated for as many 2D sections as are required to adequately define the aerofoil, normally at five sections. From this analysis the fatigue life-limiting region can be identified.

A creep assessment uses the same mechanical mesh as for the fatigue analysis, but is for either a single steady state condition or a series of steady-state conditions from a flight cycle or mission. A constant rating creep life is calculated for each of these damaging conditions, and Robinson's rule used to sum the individual rating times as a proportion of the constant rating creep life to obtain the damage fraction (Dc) i.e.

$$Dc = Dc1 + Dc2 + \dots + Dcn$$

where Dcn is the damage incurred during time at condition n.

A damage fraction of less than one is required to give an adequate service creep life for creep alone, although with the effect of fatigue interaction a value much less than one could be required.

There is a great deal of evidence to show that creep and fatigue interact to reduce the combined life of cast materials to less than the life obtained through linear summation of both the creep and fatigue damage, figure 8. A database of combined creep and fatigue test results has been developed across the full range of operating temperatures to establish the interaction curve constants. This combined life is calculated automatically using an iterative process to establish the position on the interaction curve, allowing calculation of the average blade life for the given operating mission. Weibull statistics using shape parameters for the distribution of failures from past experience in these failure modes are applied to calculate the blade set life for assessment against the Project Requirements.

Oxidation and hot corrosion assessment is performed by consideration of the operating surface temperatures around the blade. Bare and coated material behaviour has been modelled in terms of time at temperature to produce a given amount of material loss or degree of coating penetration. Using these algorithms the coating and any subsequent allowed substrate penetration life could be predicted for a given metal temperature.

3D Lifing Method

The application of 2D analysis allows the life of the aerofoil to be calculated in most cases. However there are some cases where a full 3D analysis is required. Firstly when very high surface thermal gradients exist and cause high thermal strains. Secondly for 3D blade features e.g. shroud fillets, shroud acute corners, platform to shank fillet and shank features when the elastic peak stresses and strains at these locations are required. The postprocessing to obtain the fatigue life of the 3D features is the same as for the 2D models, allowing a complex assessment of the 3-dimensional strain vector through the cycle to determine the direction and value of the maximum strain. Life assessment takes account of the 3D vector of strain around the flight cycle and will identify the worst strain cycle and consequently the minimum life for that location.

Where the features are driven primarily by mechanical loads, then consideration will be given to load controlled specimen testing material data as well as strain controlled specimen testing. Otherwise many of the other aspects remain the same as for the 2D-lifing method.

Power by the Hour Requirements

The development of a sound contract between engine manufacturer and engine operator requires not only the accurate prediction of the blade life but an efficient and timely prediction for Stage 1 of the design process, the business concept and preliminary design concept phase (7), figure 9.

During Stage 1 the market opportunities are identified for a particular engine size, the concept options are established, and from initial design analysis against a defined mission or cycle, options are downselected for preliminary design in Stage 2. This requires the use of the TBLM in the integrated system to obtain preliminary life estimates of the blade lives, where fast analysis enables the optimum cooling concept to be identified. Full 2D temperatures may not be available and therefore scaling from previous thermal solutions may be necessary. The limiting failure modes are identified for each blade and the life predicted. This information, accompanied by the cost estimates for manufacture of the blade, is used in the life cycle cost estimate. Each concept can then be reviewed with respect to the initial unit cost and the life cycle cost of the individual blades, and summated to determine the module life cycle costs against the Project Requirement. Further design iterations and life estimates must be made where these costs are unsatisfactory. The prime concept is selected and the design moves into Stage 2, the 'Full Concept Definition' phase.

In Stage 2, more detailed aerodynamic definition, cooling analysis and geometry definition is carried out. Steady

state and transient thermal behaviour is predicted and more detailed life estimates made, again requiring fast and accurate life estimates. The rapidity with which life estimates can be made is clearly demonstrated by the fact that with the input information available (e.g. temperatures, material properties etc.) for a 25 point transient cycle, a creep analysis, fatigue analysis and full life assessment can be made in less than one hour for a single 2D section. This includes creep-fatigue interaction life prediction at each node of the model.

The design proceeds into Stage 3, which is the 'Propulsion System Realisation' stage. Blades are validated in rig and engine tests, not only to demonstrate the performance characteristics but also to demonstrate the blade life capability through accelerated endurance tests. The TBLM is applied to assess the component damage that will occur during the test, and to make revisions to the test programme. The life is predicted prior to the test, and then recalculated by a back analysis at the end of the test when the actual engine performance has been measured. In this way an accurate picture of the life capability of the blade is built up.

Stage 4 is reached when the engine enters service. Throughout the assessment of life made so far the accuracy of the predictions has been dependent on the assumed engine operating conditions in service. Therefore, from an engine manufacturer's point of view, the essential element for confirmation of blade life is verification of not only the blade damage accumulation, but also the engine operating behaviour. This can be achieved by monitoring of engines as far across the fleet as possible. The results of the life assessment will be compared with service experience on these components to show how the blade is meeting its design requirement. Engine operators will also benefit significantly from monitoring of engine behaviour because this will enable them to understand how the damage usage is accumulating for individual missions, and how planned maintenance will effect their fleet operation.

Measurement of Life Usage

It is essential that the life usage computation should mirror the design computational method to achieve life usage measurement to an acceptable degree of accuracy. This section describes the processes undertaken within a damage counter system and applies equally to an airborne or ground based system. The general procedure is as follows:

At each time point,

1. Sample performance data signals
2. Derive additional performance parameters
3. Calculate blade stresses, strains and temperatures for the predicted failure positions
4. Isolate stress and strain extremes
5. Extract cycles by modified TREND method
6. For critical components, convert cycles to 0-max equivalent damage cycles
7. Ascertain if cycles are damaging
8. Accumulate damage

The actual measured performance data signals will vary from one engine type to another and with different operations, but will generally include those parameters identified in figure 10.

Performance algorithms are used to derive parameters that cannot easily be measured directly. These can take the form of equations or look up tables.

Analysis models used during the design phase to calculate transient temperatures and stresses require substantial computational power and storage and can only be effectively used on a workstation installation. The major restraint on service monitoring operation however, is the requirement to operate on a mini-computer at a maintenance base, or on-board microprocessor. It is therefore necessary to construct a simplified transient heat transfer/stress analysis model that represents an acceptable compromise between computational power limitations and accuracy. The model is then scaled based on datum temperatures and stresses to temperatures and stresses for each condition. A description of the failure mode damage assessment follows.

Creep Damage

Creep damage is computed from an algorithm that describes the creep strain behaviour with time. Graham and Walles is used to relate creep damage (Dc) to temperature (T) and stress (σ) through the relationship:

$$Dc = k_4 * (\sigma^{k_5}) * \Delta\theta / (k_6 - T)^{20}$$

where k_4 , k_5 , and k_6 are material dependent constants

$\Delta\theta$ is the time spent at condition.

This creep damage is then summated during the mission in accordance with Robinson's rule.

Creep damage calculation requires knowledge of the stress (σ) at every steady state condition n . This stress is scaled as being proportional to the square of the measured HP shaft speed (NH^2), and is related to the datum speed and the stress obtained from the detailed design calculation.

The blade temperature (T_n) is scaled from the design value using a non-dimensional relationship involving the local gas temperature (T_g) and cooling air temperature (T_c). Cooling air temperature (T_c) is linearly related to the compressor delivery temperature (T_3), and the local gas temperature is linearly related to the stator outlet temperature (SOT) at exit from the combustor. T_3 is a function of the two measured parameters, NH and intake temperature (T_1). SOT is a function of the measured jet pipe temperature (T_5) and the intake temperature (T_1), or may be derived directly from a pyrometer measurement of the blade aerofoil temperature (TBT) and knowledge of the cooling effectiveness at the measurement point.

Thus from the measured parameters NH , T_1 , and T_5 , a knowledge of their interrelationship, and a detailed design estimate of the creep life usage, the turbine rotor blade creep life usage can be computed at any condition encountered in service.

Low Cycle Fatigue

Traditionally, low cycle fatigue on a blade has been referred to in engine monitoring circles as thermal fatigue

in order to distinguish it from LCF of Critical group A parts. Thermal fatigue life usage is derived from a knowledge of the strain range ($\Delta\epsilon$) experienced by the elements of the turbine rotor blade when cycled from one condition to another.

Notionally, the thermal fatigue damage (Df) is a function of the strain range and temperature (T) at the maximum temperature in the cycle. They are related by an algorithm of the form:

$$Df = 1 / Nf \quad \text{and} \\ \text{Log } Nf = \text{Log } Nf_{\text{datum}} - (\text{Log } (\Delta\epsilon_{\text{datum}} / \Delta\epsilon) / k7)$$

where $\text{Log } \Delta\epsilon_{\text{datum}}$ and $k7$ are material constants, each of which has a temperature dependency, and Nf is the number of cycles to failure.

The thermal fatigue damage can be linearly summated in accordance with Miner's rule. The method of cyclic extraction is the same TREND method as used in LCF cycle extraction. Nf is then dependent upon local element metal temperature, and the strain range through which the element is cycled. The strain range is computed by separating out the strains due to each type loading. Each of these constituent strains is then scaled from the datum design cycle by the use of the appropriate parameters, after which they are re-summated at the new cyclic condition.

The calculation of each cyclic strain range requires the parameters HP shaft speed (NH), HP compressor delivery pressure (P3) and compressor inlet temperature (T1). Whereas the creep damage summation could be achieved by using steady state temperatures, thermal fatigue damage summation requires transient temperature variation around the cycle to be determined. This is determined by a relationship between local response rate of the element to changes in temperature, and the interval between sampling. The turbine rotor blade metal temperature response rate at any condition is calculated from knowledge of the turbine gas mass flow rate, which can be calculated from the measured parameters. Thus, using the additional measured parameter (P3), and knowledge of the interrelationship with the parameters measured to compute creep life damage, the thermal fatigue life usage can also be monitored.

Oxidation

Oxidation life usage monitoring is similar to creep damage assessment. The local temperature is computed in the same way as for creep life usage computation, without the need for additional parameter measurement. The rate of oxide penetration into the material or coating with time uses the oxidation life algorithm used during the analytical phase. The oxidation life usage is summated during the service life assuming a linear damage relationship.

Power by the Hour Requirements

Relatively simple programmable algorithms allow the prediction of the life usage of turbine blades from a few aircraft and engine parameters. This operational life usage has been calibrated to reproduce the life usage that would be predicted by the more precise, but computationally more demanding design methodology. Algorithms specific to a

particular application are validated against engine bench programmes of accelerated simulated mission endurance tests or type tests, formulated to validate the engine against its operational design requirements. There is also the capability to modify the algorithm constants in the unlikely event of a service-demonstrated anomaly.

Simultaneous development of the engine monitoring hardware and electronics has provided a sophisticated means of operational life monitoring of turbine blades and allowed more precise prediction of life usage. This, in turn, has allowed life extension of these blades without jeopardising safety requirements. The precise prediction of life usage has led to a reduction in cost of ownership by providing a tool for more accurately planning maintenance and inspection intervals whilst at the same time reducing the probability of premature failures thus optimising power by the hour requirements.

It has also provided the engine manufacturers with a more accurate means of determining actual mission and service loads, which in turn has allowed more realistic power by the hour evaluations, and allowed cost savings through more realistic parts provisioning programmes.

Conclusion

This paper has reviewed how 'Power by the Hour' contracts require accurate turbine blade life prediction to establish meaningful and sound contracts. The advanced system employed by Rolls Royce for the assessment of turbine blade life has been described and its merits outlined. The requirement for engine monitoring in these contracts has been described and the benefits for both the engine operator and engine manufacturer described. 'Power by the Hour' contract fulfilment requires both the analytical tools and monitoring methods to be part of a fully integrated lifing system, which has been demonstrated. The future holds the increasing application of smart computer technology - someday the engine measurement system will tell the operator when a part needs to be changed!

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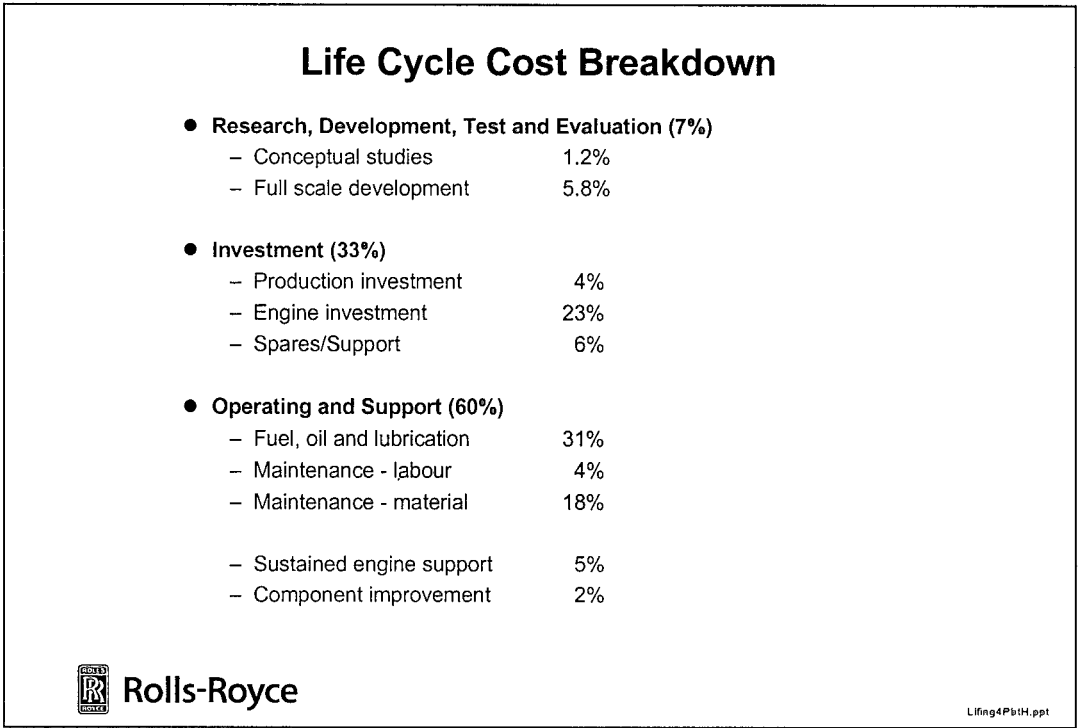


Figure 1

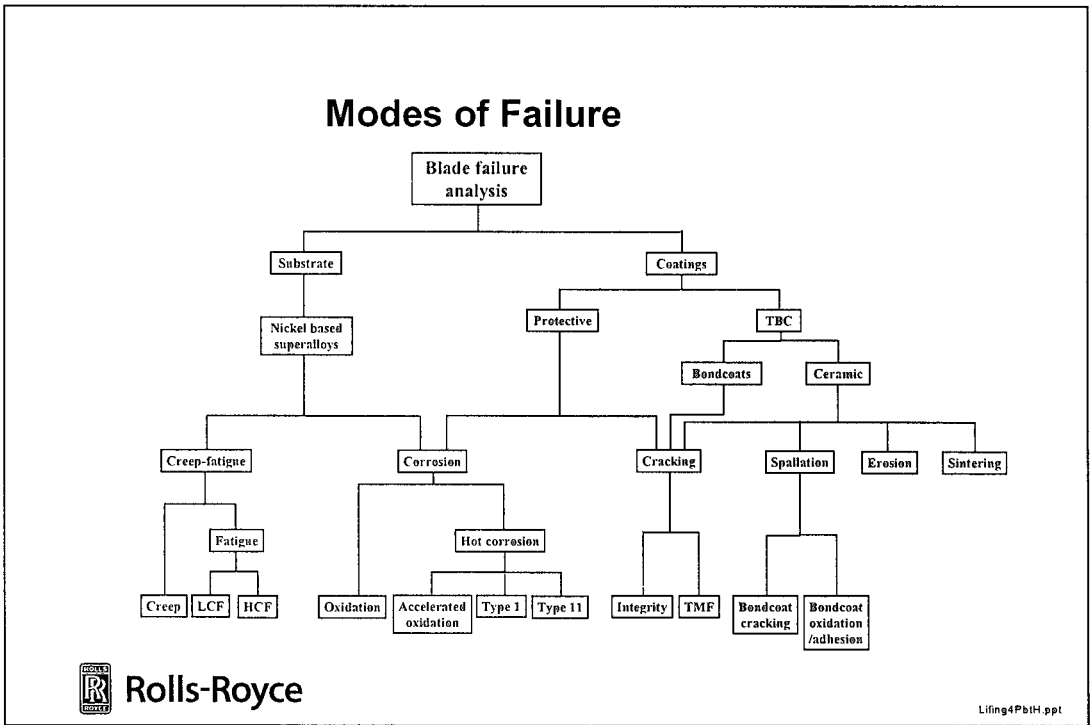
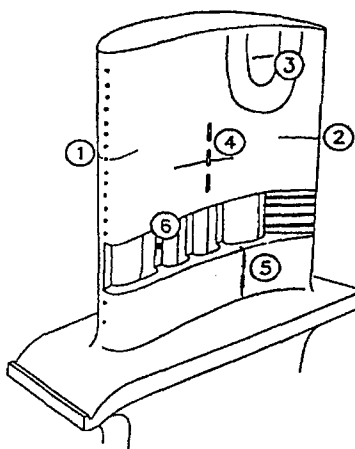


Figure 2

Potential Low cycle Fatigue Failure Locations

1. Leading edge holes, chordal cracking
2. Trailing edge holes chordal cracking
3. Hotspots, any location
4. Pressure surface film cooling holes, chordal cracking
5. Pressure surface film cooling holes, radial cracking
6. Cold web cracking

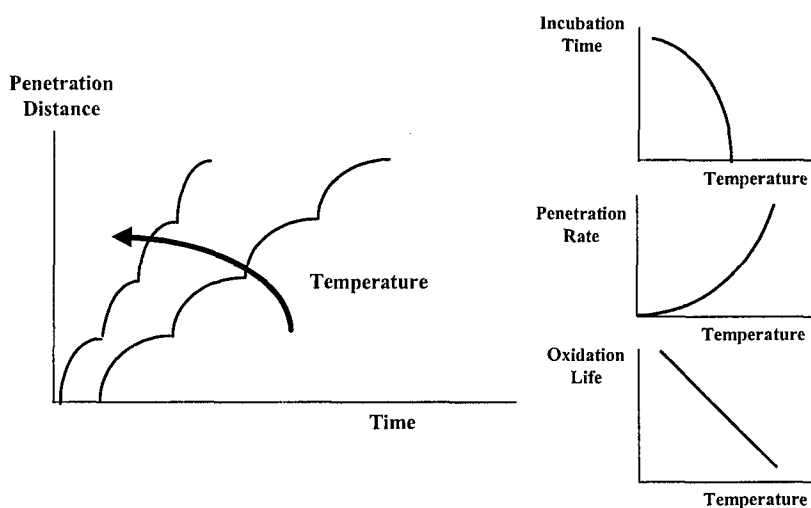


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Figure 3

Surface Attack - Oxidation



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Figure 4

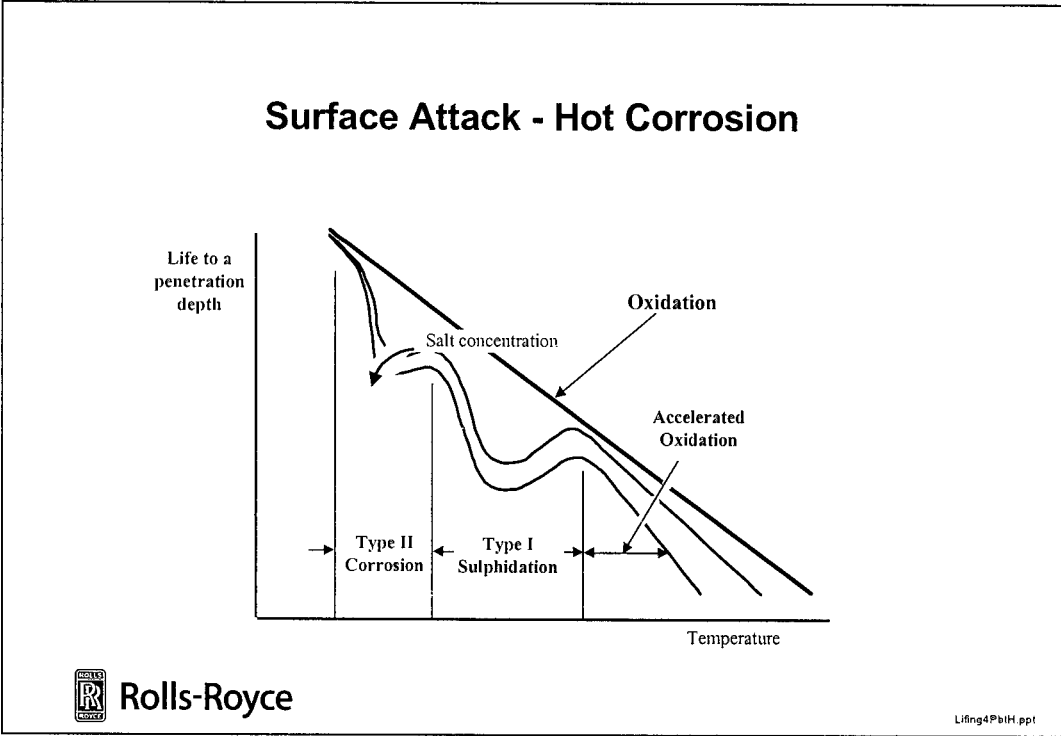


Figure 5

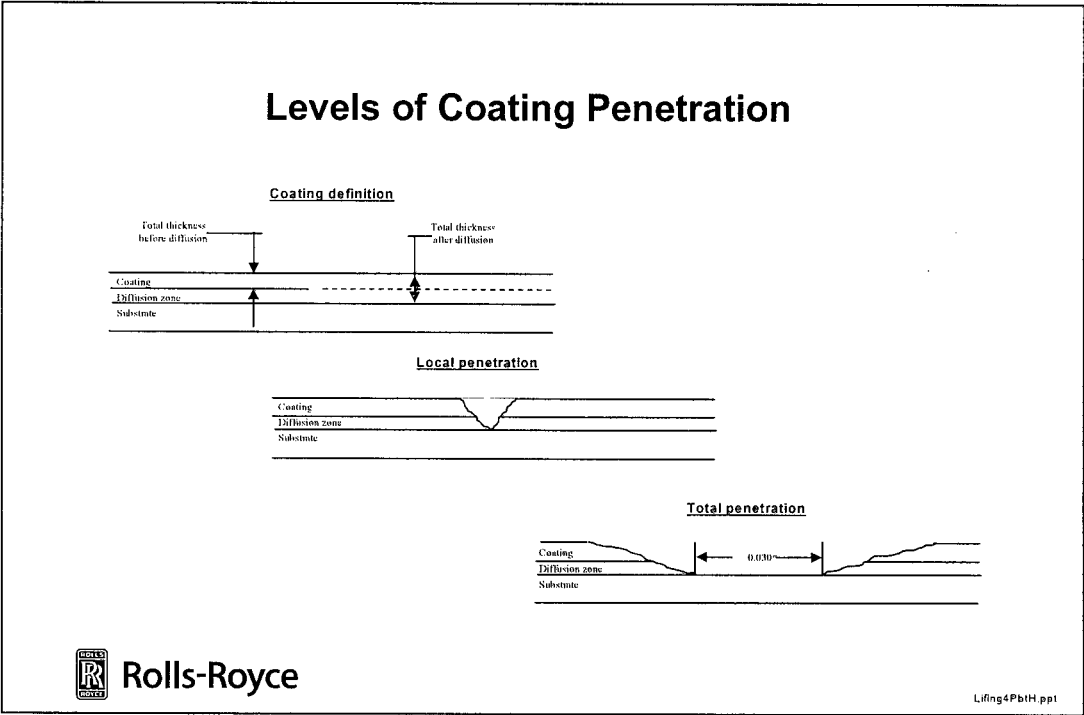


Figure 6

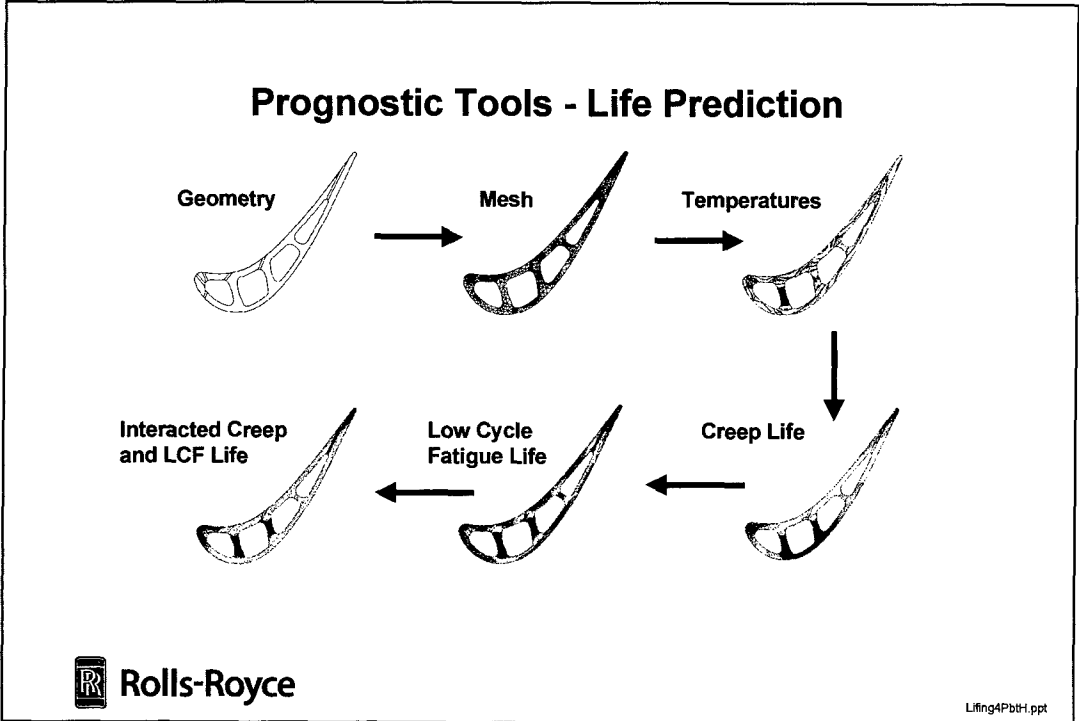


Figure 7

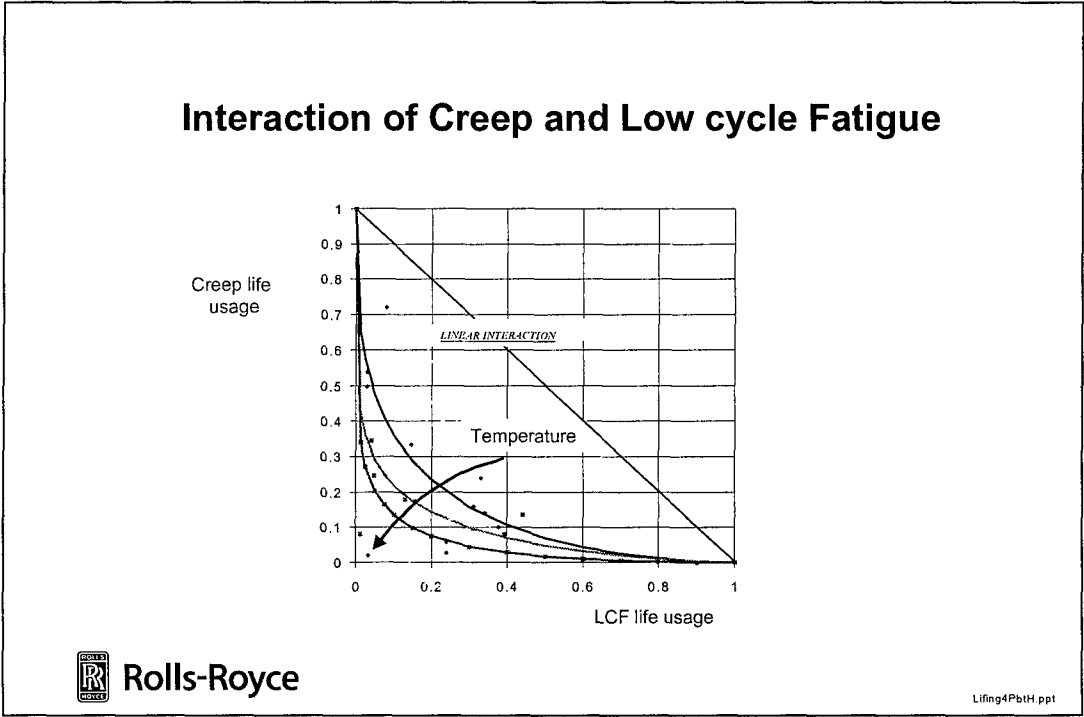


Figure 8

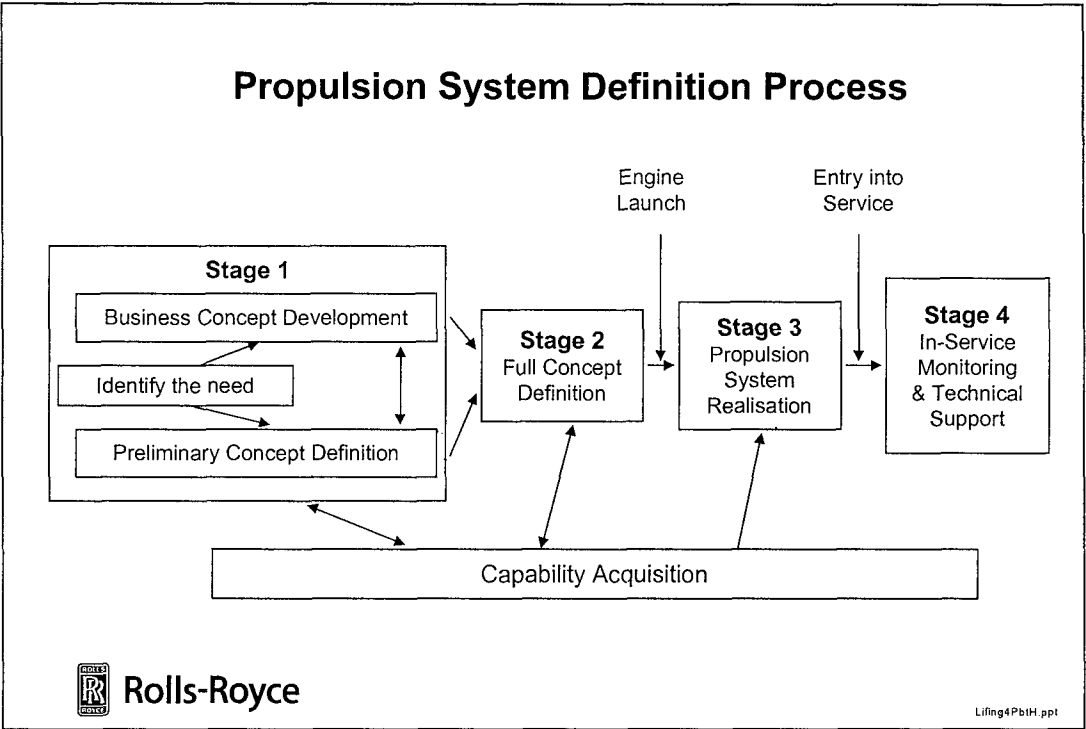


Figure 9

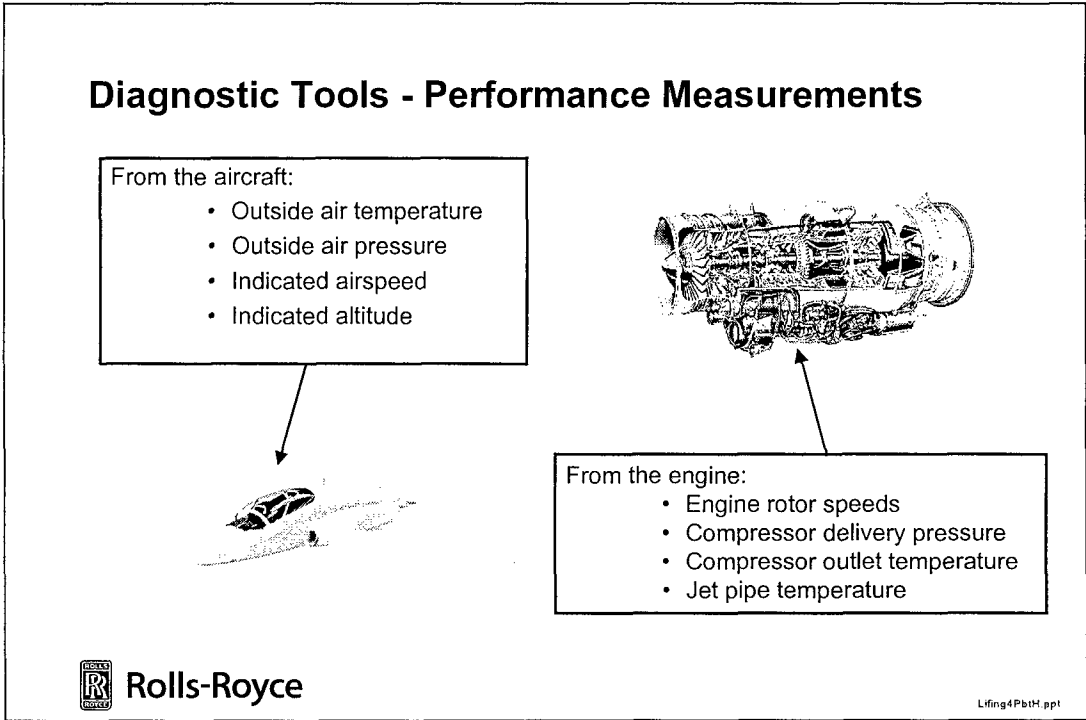


Figure 10